Darpa Contract MDA972-92-C-0075

OETC Optical Backplane Bus Testbed

IBM Tasks: Receiver OEIC and Link Simulation Tools and Analysis

Contract Deliverable Items

#000103	First Pass Link Simulation Results (Task I.2)
	First Pass Link Specifications
#000104	First Pass Receiver Specification and Design Review (Task I.1)

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OETC Optical Backplane Bus Testbed

IBM Milestone Technical Report

Optical Link Simulation

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Executive Summary

This milestone report describes the strategy adopted for developing a bus simulation tool; the parameters chosen for the component models which are used in the tool; the experimental determination of the parameters for one of the key devices in the link, the VSEL; and the experimental and simulation analysis used to predict the first pass link behavior.

The major accomplishments of this milestone report are that (1) a set of specifications were developed by Martin Marietta Corp. (MMC) using the IBM link simulation tool, as well as discussions with the component suppliers; and (2) that a design for the VSEL source for the transmitter was established based on device and link characterization at IBM. Operational parameters for the transmitter simulation model were also developed. With these accomplishments, first pass components for the link can,and are, being designed and fabricated.

The bus simulation strategy adopted is to essentially treat buses as statistical ensembles of separate links. Statistical variations of the nominal parameters describing each component in the link need to be measured (using first pass parts) and added to the link model. The overall bus performance will be determined by the 3 sigma worst case performance of the 32 links in the bus. Crosstalk terms will be added to the models (based on measurements of first pass parts) to account for any correlation between individual link performance in the bus. The IBM OLAP link simulator was therefore modified to account for statistical variations in component parameters during this milestone period.

The nominal parameters for the VSEL were not available, so IBM characterized AT&T VSELs to establish a design and determine parameters for the component model.

Modal noise was determined by IBM analysis to be the major limitation to reliable link performance, so special experimental and statistical simulations were done to assure that there were no noise floors in single link behavior using OETC components.

The amount of high speed experimental support work required by IBM to get the OETC first pass, plan-of-record link nominal component parameters evaluated was significant. Although IBM is not responsible (under the OETC contract) for developing component designs (except for the receiver chip) or performing experimental link evaluation, it appears that IBM is the only OETC team member with available equipment and experience to perform AC component, link, and bus characterization tasks on the OETC schedule. This is an issue for MMC to address in their system integration and testbed fabrication responsibilities.

Introduction

This report describes the first pass link analysis made using the OETC components being developed for the OETC testbed bus. Developing the models for the link and bus simulations, and performing the simulations in order to predict link and bus performance is an ongoing process, involving the contributions of Honeywell and AT&T in component models, and involving Martin Marietta (MMC) in bus design specifications. This milestone report is thus more of a status report. Its significance is that the first pass components for the OETC bus are being designed and fabricated based on the analysis provided in this report.

The OETC proposal to ARPA contained a rough power budget for the links, assuming a worst case, typical, and best case set of values for the components and adding significant margins for noise sources into the budget. This link budget, shown in Figure 1, resulted in a spread in link margins from -2.5 dB to +21.5 dB. Therefore, in the worst case the link was inoperable; and even in operable cases there was a huge range in possible performance.

Allowing such a range of performance makes it very difficult to do efficient (low power) component design, especially in the receiver which must accommodate the possibility of a huge range in input power and still deliver reliable digital output from all lines across the array. Thus, the first task of the OETC design project was to use experiments and simulations to narrow the range of expected performance. The objectives in this milestone report are show a better understand the actual noise sources and their influence on link BER, to show that a link can be designed for low error rate in the worst case, and to narrow the dynamic range in the link.

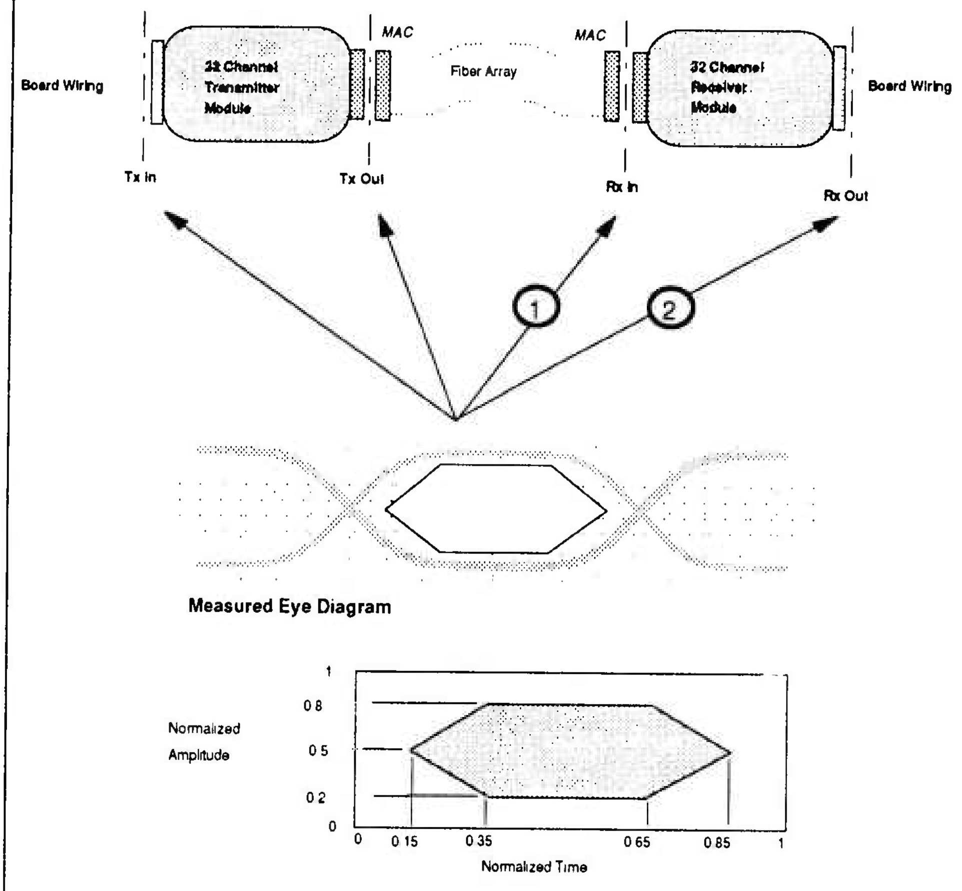
Figure 1 - Link Power Budget as proposed in the OETC DARPA proposal 12/91

	SEL	Based	Xmitter	Modulator	Based	Xmitter
	Best case	Typical	Worst case	Best case	Typical	Worst case
Transmitter Losses						
Laser Optical Output Power	+3 dBm	0 dBm	- 6 dBm	+20 dBm	+18.5 dBm	+17 dBm
Coupling to chip	-	-	-	-2 dB	- 3dB	-4 dB
1:4 Split						
Excess Splitter Loss						
Modulator Waveguide Loss	-	-	-	-1 dB	-2dB	-3 dB
Modulator Loss	-	--	-	0 dB	2 dB	-2dB
Bend Loss	-	-	-	-1 dB	-3 dB	-5 dB
Coupling to Waveguide	-1 dB	-2 dB	- 3 dB	- 0.5 dB	- 1 dB	-2 dB
Connector Loss	- 0.5 dB	- 0.5 dB	-1 dB	- 0.5 dB	- 0.5 dB	- 0.5 dB
Total Transmitted Optical Signal Power	**+1.5 dBm**	**-2.5 dBm**	**-10 dBm**	**+7 dBm**	**-3 dBm**	**-12 dBm**
Link Losses						
Optical Waveguide Loss	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB
Optical Connector Loss	- 0.5 dB	- 0.5 dB	- 1 dB	- 0.5 dB	- 0.5 dB	- 1 dB
Coupling to Detector	0 dB	-1 dB	-2 dB	0 dB	-1 dB	-2 dB
Optical Cross-talk						
Total Received Optical Signal Power	**+ 0.5 dB**	**-4.5 dB**	**-14 dB**	**+6.5 dB**	**-44.5 dB**	**-15 dB**
Receiver Penalties						
Extrapolation to BER = 10^{-15}		1.5 dB			1.5 dB	
Electrical Cross-talk Penalty	0.5 dB	1.5 dB	2 dB	0.5 dB	1.5 dB	2 dB
DC off-set penalty	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB
Modal Noise Penalty	0 dB	2 dB	3 dB	0 dB	2 dB	3 dB
Jitter Penalty	0 dB	1 dB	1 dB	0 dB	1 dB	1 dB
Dispersion Penalty		0 dB			0 dB	
Skew Penalty	0 dB	1 dB	2 dB	0 dB	1 dB	2 dB
Total Penalties	- 2dB	-7 dB	-9.5 dB	- 2 dB	- 7 dB	- 9.5 dB
Receiver Sensitivity for BER = 10^{-9}	- 23 dBm	-22 dbm	-21 dBm	-23 dBm	-22 dBm	- 21 dBm
Receiver Sensitivity after Penalties	- 21 dBm	- 15 dBm	-11.5 dBm	-21 dBm	-15 dBm	-11.5 dBm
Link Margin	**+21.5 dB**	**+10.5 dB**	**- 2.5 dB**	**+27.5 dB**	**+10.5 dB**	**-3.5 dB**

The OETC bus simulator tool development plan is to adapt a version of the IBM OLAP program, together with supplementary programs, to make a bus simulation tool. Models of the transmission code, laser driver chip, VSEL laser array chip, link cable and connector, and receiver array chip are to be provided by the component developers. These models are to be inserted into the link simulator and a prediction of the link bit error rate (BER), as well as a sensitivity analysis to parameter variations, is to be made.

IBM proposed, and it was accepted by the OETC, to define component specifications at the interfaces between components, as illustrated in Figure 2. Thus the details of a component (e.g. whether a transmitter is a VSEL array or a Modulator array) do not have to be known at the system level. The specifications are determined based on the component delivering acceptable eye closure at its output, given a certain eye at the input. The eye is measured by a standard eye template, a procedure adopted by the ANSI Fiber Channel Standard, and illustrated in Figure 2. The first component models were to be based on nominal values of the parameters needed to characterize the components. If possible, parameter statistical and environmental variations were to be provided, so the worst case as well as nominal link performance could be simulated. The purpose of this link simulation was to provide some confidence to the component developers that the first pass parts, if successfully fabricated would form a working link.

Figure 2- Interface definitions



Eye Mask Specification

However, it became apparent during the first two quarters of the OETC program that there was not sufficient data on all the bus components to determine even the nominal parameters of the components. Therefore, test vehicles were designed, fabricated, and characterized in order to get better ranges for some component performance. Nevertheless, it was concluded that first pass parts needed to be designed and fabricated in order to obtain functional parameters for some of the components.

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Technical Approach To Simulation Tool Development and Status

The strategy for developing an optical bus simulation tool is as follows :

1. Use the IBM OLAP link simulation tool, running on a host computer, as the basis for an optical bus simulation tool. Use existing parameter input and anaysis output formats.

2. Simulate the OETC optical bus by treating the bus as a statistical ensemble of 32 links. Each link component will have statistical variations added to their nominal parameter specifications, accounting for uniformity in fabrication, temperature fluctuations, and variations in bias conditions. Initial Bus performance would be simulated as the 3σ worst case of the 32 links.

3. When first pass parts are measured, and device and link crosstalk and interaction are determined, add terms accounting for the correlation between links to a second pass bus simulation tool.

Model Development Status

Models for the following components were available and put into the OLAP simulator (if not already present):

- **Signal Generators, Codes**
  - Manchester encoder and decoder
  - Psuedo-random sequence
  - Square wave for clock simulation
  - Special programmable patterns for testing
- **Transmitters**
  - F-P Edge emitting laser
  - LED
  - *MESFET driver chip have not been added due to lack of parametric data.*
  - *VSEL and QW Modulator models have not been added due to lack of parameters.*
- **Interconnects**
  - 62.5 μm core diameter, GI multimode fiber, 160 MHz-km BW at $\lambda = 0.84$ μm.
  - Connector with uniform and mode selective loss
  - *Waveguides have not been added due to lack of parametric data.*
- **Receiver**
  - MSM-PD
  - MESFET transimpedance amplifier
  - Manchester decoder

The models were enhanced to account for nomianl and statistical variations of parameters.

Parametric data used for the components in the OETC link simulations were determined. Appendix A lists the parameters used for first pass link simulation. Data not available is noted.

The following analysis output modes have been incorporated into the OLAP simulation tool.

Spectral power density, Statistics of Codes, Pulse Diagrams, eye diagrams, BER vs. Received optical power, Noise pie charts, Receiver frequency response, timing offset penalty. *Analysis of crosstalk and multichannel skew have not been put into the first pass simulator.*

Experimental Results on AT&T VSEL Characterization

The OETC concluded that the transmitter using a VSEL laser array was the up-front transmitter design, so that developing a model for this component was of prime importance. The model for a MESFET OEIC receiver and for cables and connectors were already available (to first order).

The VSEL laser array was the link component with the largest potential variations in performance, and thus had largest effect on the overall link power margins. Therefore, it was decided to concentrate on this component. The design point in terms of modal spectrum, threshold current, slope efficiency, and noise sources had not been established by AT&T. IBM and AT&T therefore collaborated on DC and AC characterization of two candidate VSEL devices. The characterization stations at IBM were used, because the high speed optical and electrical measurement equipment and probe stations were already in place, and because IBM had experience in laser characterization for data bus applications. The emphasis in characterization was on noise and skew characteristics, as these were expected to be more important in determining bus BER (bit error rate) performance.

Two device designs were considered, a multi-transverse moded VSEL, labeled 25I/10W, and a single moded device labeled 20I/5W. The former is more robust in practical design (repeatable characteristics device-to-device), but is less efficient overall, at low power levels, and more variable in skew.

25I/10W Characterization (Multimoded VSEL)

Figure 3 shows the P-I-V curve for the 25I/10W device; the lower P-I curve is for the light coupled into a 50/125 µm fiber positioned 100 µm above the SE-LD. The coupling efficiency was good, but not quantitatively characterized (see AT&T progress reports on coupling to 62.5/125 µm fiber). Figure 4 shows the relative intensity noise (RIN) at 500 MHz, as a function of bias current. The RIN was comfortably below -120 dB/Hz once the laser is biased more than 0.5 mA above I_{th}, although it fluctuates due to the multi-moded nature of the device and due to optical reflections from the fiber endface.

Figure 3. P-I-V for 25I/10W SE-LD

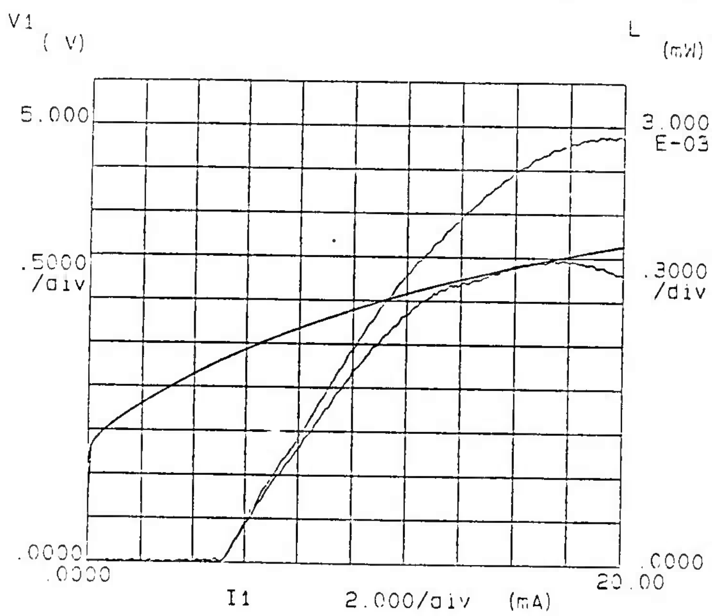


Figure 4- Relative Intensity Noise at 500 MHz for 25I/10W SE-LD

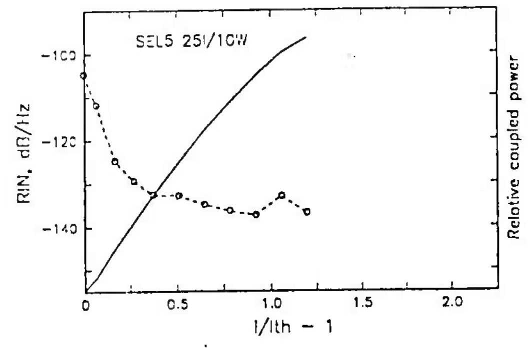


Figure 5 shows the optical spectrum for the 25I/10W device design, measured CW at 6,8,10 mA bias. The device displays a large spectrum and low coherence, particularly at higher bias current. Therefore, it is expected to demonstrate low sensitivity to mode -selective loss- a desirable feature for low link BER.

Figure 5- Optical spectrum at 6,8,10 mA for 25I/10W SE-LD

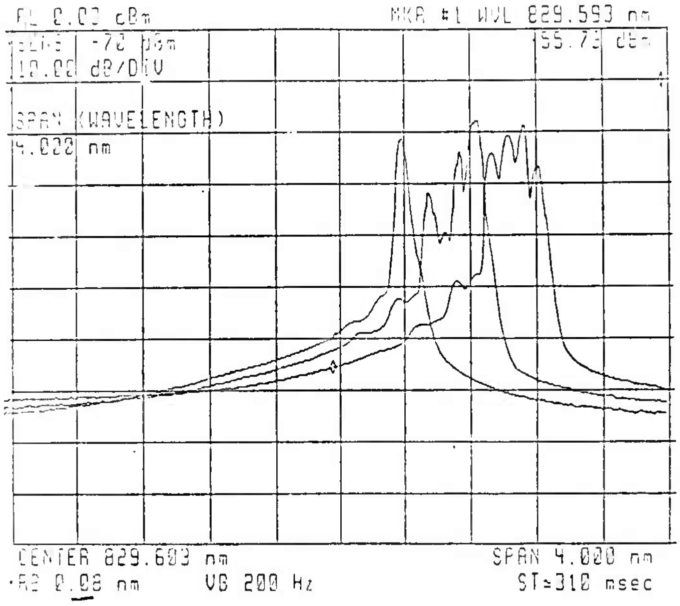


Figure 6 shows the small signal frequency response of 25I/10W, measured at 5.25, 5.5, 5.75, and 6 mA bias. The relaxation frequency increases with bias, as expected, being approximately 2 GHz at 5.75 mA, and adequate for the OETC application. .

Figure 6- Small-signal frequency response at 5.25, 5.5, 5,75, and 6 mA for 25l/10W SE-LD.

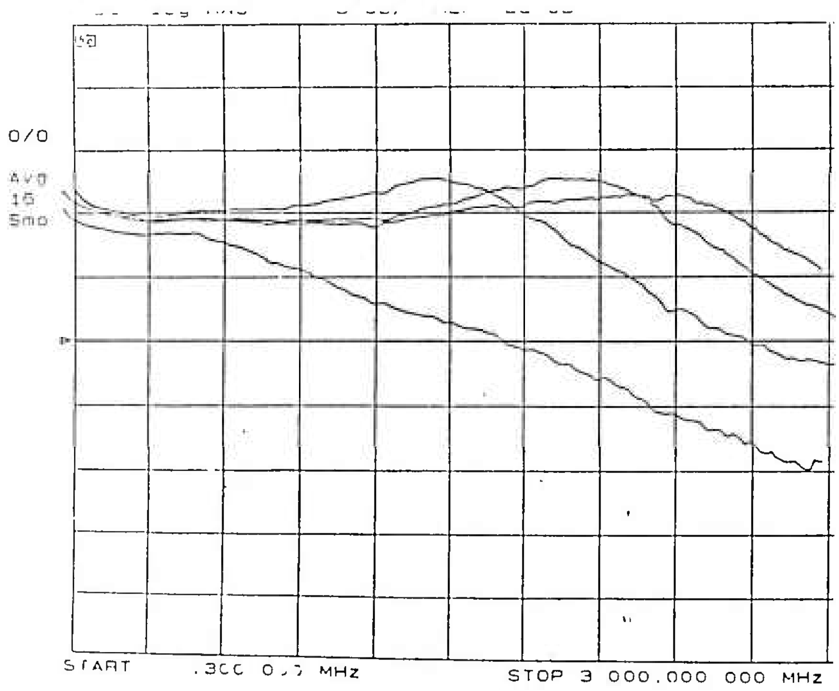
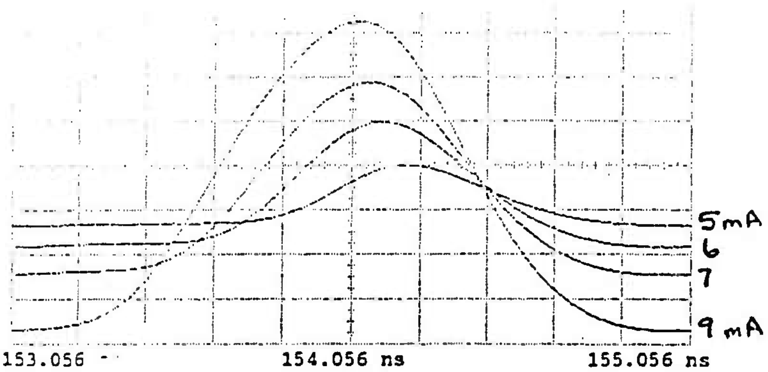


Figure 7 shows the effect of different bias conditions on the laser turn-on delay. The upper result is for 10 mA p-p square wave modulation about an average bias of 5,6, or 7 mA. The time axis is 200 ps/div. These results indicate that some laser pre-bias is essential, to minimize skew, with the relative high threshold of this device. This will be a negative feature, due to the added heat generated in the array. Figure 7b also shows the effect of bias on skew, but with a ± 3 mA '101001' modulation. Again, a bias point between 9-12 mA is recommended.

Figure 7- B[illegible]ondent skew
(a) 10 mA sq[illegible]ave modulation with 5,6,7,9 mA bias for 25I/10W SE-LD



(b) ±3 mA '101001' modulation with 7, 7.5, 9, and 12 mA bias for 25I/10W SE-LD

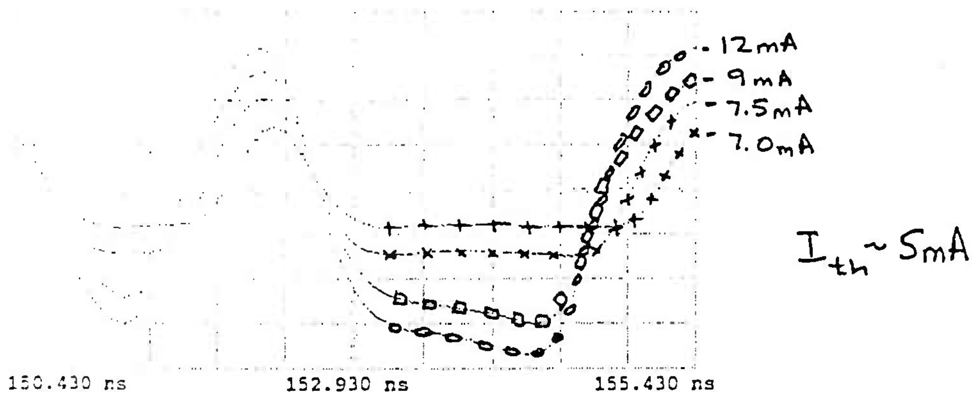
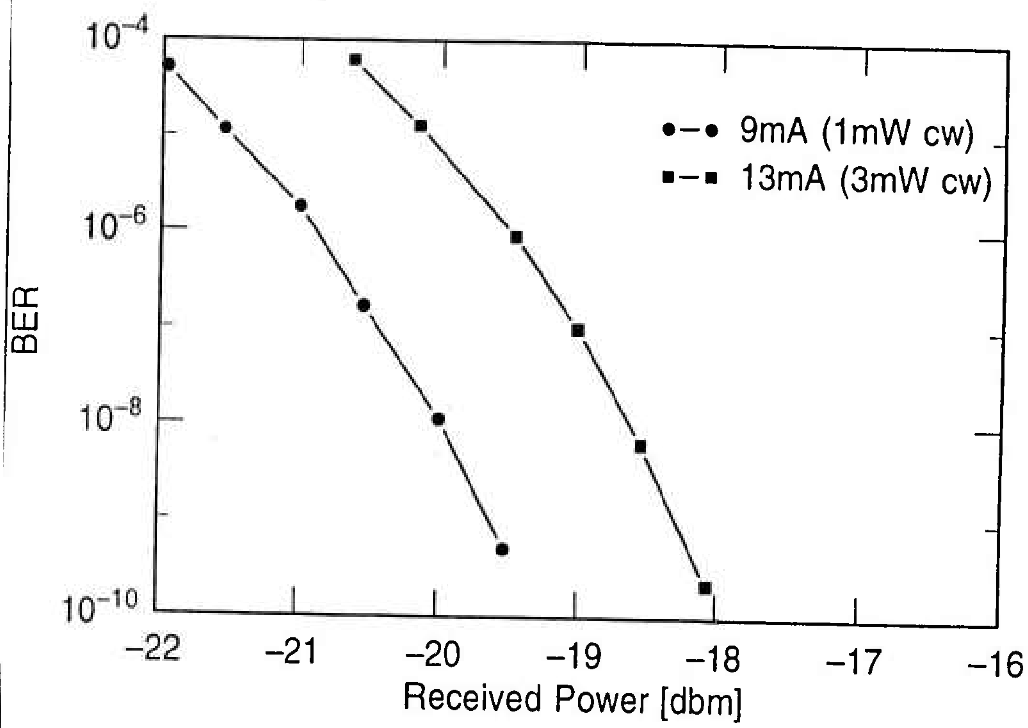


Figure 8 show 1 Gigabit/sec link BER measurements for a link using a different multimode VSEL, 25I/25W. The VSEL has two transverse modes at 1 mW coupled power and four transverse modes at 3 mW coupled power. Note that neither demonstrate a BER floor down to BER= 10^{-10}, leading to the conclusion that it is a suitable candidate for the oETC optical bus. The 1.5 dB offset in the curves is due to a change in the extinction ratio of the modulated light (leading to different link noise).

Figure 8- Link BER versus received power using a VSEL of 25I/10W design



AT&T 25W/25I VCSEL

Even though this laser appears suitable for the OETC bus, AT&T has concluded that ultimately it will reauire higher current, leading to excessively high power dissipation in a VSEL array. Also the unstable transverse mode operation under modulation was a concern as it might lead to variable coupling efficiency to the fiber - an AC noise source in the link. This should be revisited when the lasers are packaged in the array module. Nevertheless, it should be pointed out that, at this point in the maturity of the VSEL, the lower series resistance of the multimode VSEL, and the more stable link operation may make it actually the more efficient emitter to use (as it was in our measurements).

20I/5W Characterization (Single-mode VSEL)

It is anticipated by AT&T that the single mode VSEL device will eventually be the more efficient emitter, and thus it was characterized for suitability in the OETC link.

Figure 9a indicates a typical P-I-V curve for the 20I/5W device design. The lower curve is for the light coupled into a 50/125 µm fiber positioned 100 µm above the VSEL. As in the multimode SE-LD case, the RIN is also below -120 dB/MHz once the laser is biased > 0.5mA above threshold , Figure 9b.

Figure 9- (a) P-I-V curves for 20I/5W (b) RIN measurement

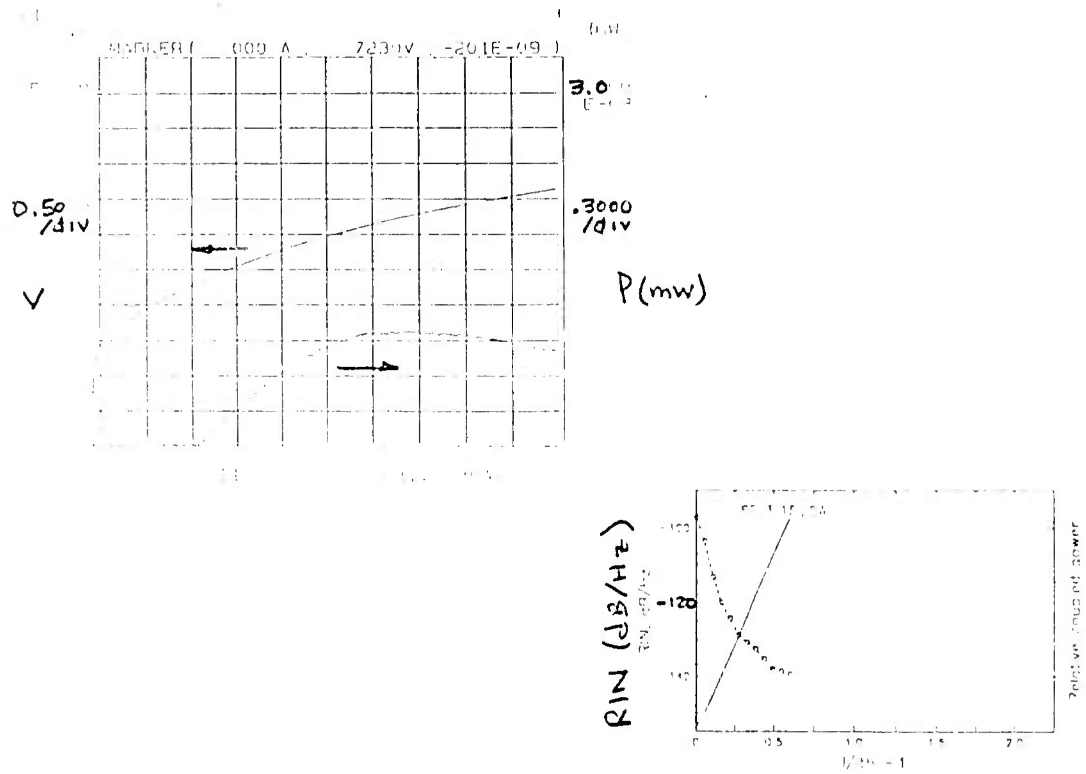


Figure 10 shows the optical spectrum with 3 mA of Gbit/s psuedorandom modulation, on bias currents of 6.5, 8, 9 mA. Even for the highest bias condition, the time-averaged higher order transverse modes are at least 45 dB below the main mode. There was a slight line shape variation with bias point.

Figure 10- Optical spectrum of 20I/5W. 10 dB per vertical c

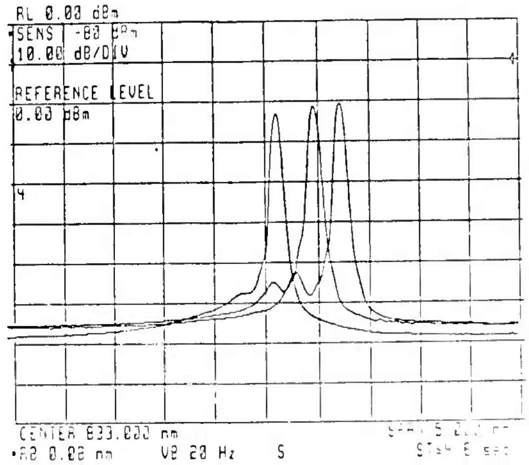
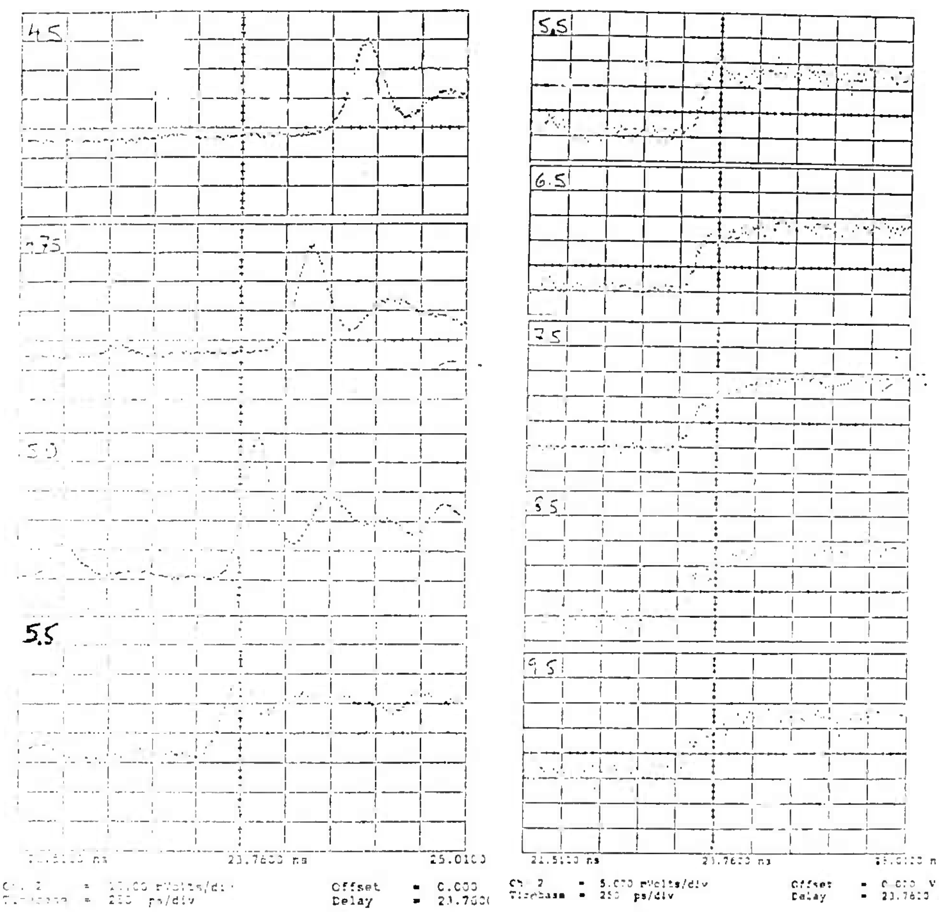


Figure 11a shows the effect of different bias conditions on the turn-on delay of 20I/5W. The results are for 1 mA peak-peak square wave modulation, about an average bias of 4.5 to 9.5 mA. The time axis is 250 psec/div. As in the multimode case, prebias is necessary to prevent skew in turn-on delay. Figure 11b shows the same experiment using Manchester coded data patterns, ± 1 mA modulation depth on 4.5-8 mA bias. Note that for the single-mode VSEL, a bias of about 5.5-6 mA is adequate for bus skew considerations, about 40-50% lower than for the multimode case.

Figure 11- Turn on delay versus bias point for 20I/5W
(a) Square wave modulation



(b) ± 1mA Manchester modulation on 4.5-8 mA bias

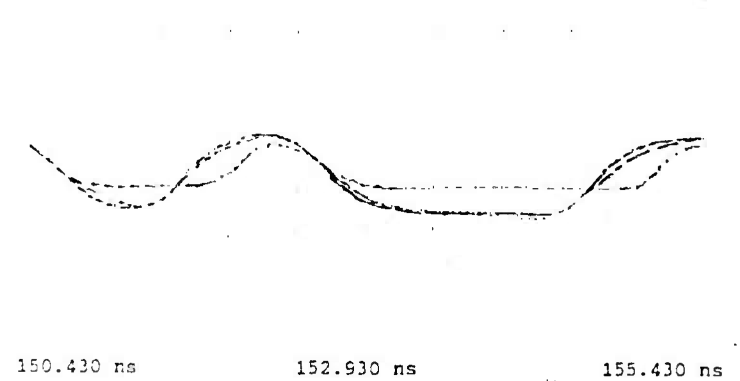


Figure 12 show the effects of large signal modulation on skew performance. Thus it is concluded that a high bias point is necessary, and that large signal modulation is not sufficient to supress skew.

Figure 12- Turn on delay for large signal , ±4.5 mA modulation on 4.5 mA bias for 20I/5W SE-LD

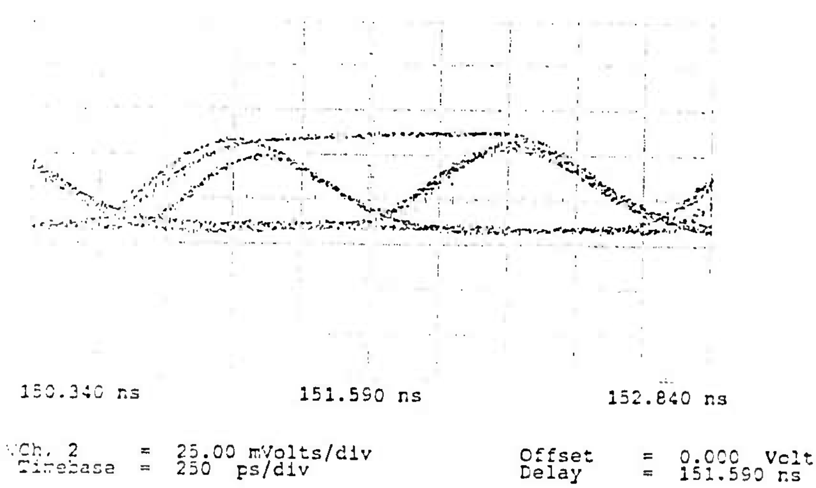
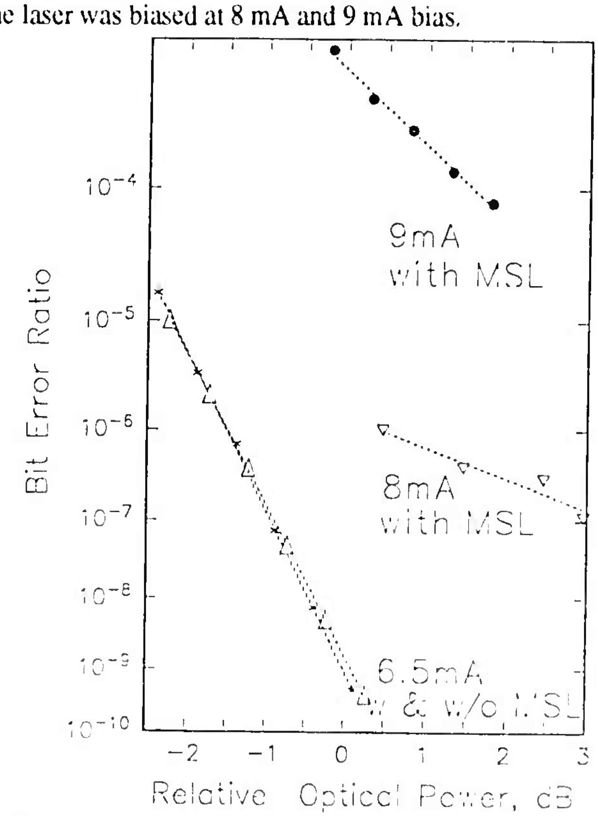


Figure 13 shows the measured BER versus received optical power for a test link using the 201/5W device, at three different bias points, and two different amounts of mode selective loss in the link. The mode selective loss (MSL) is obtained by purposely misaligning a connector 5 meters downstream from the laser (it may also occur due to inefficient coupling between laser and fiber). A 1 Gb/sec PRS with ± 1.5 mA laser modulation was used. A large MSL introduced BER floors (due to modal noise) even though the laser was nominally single mode. It is thought that this noise arises from the occasional appearance of higher order transverse modes in the laser, causing changes in the speckle pattern. This is evident from the BER floors seen in the link with MSL, when the laser was biased at 8 mA and 9 mA bias.

Fig. 13



Link Simulation Results

The first pass simulation of a single link performance assumed the characteristics of laser design 201/5W, and the other components of Appendix A. The power margins in the link were found to be more than adequate if the operating parameters of the VSEL could be controlled to nominal values. The effects of modal noise were expected to lead to a need for extra power margin. Therefore the link simulation work focused on quantifying the statistical probability of modal noise induced link penalty, and especially the avoidance of BER floors, assuming a range of expected mode selective loss mechanisms from link connectors and module coupling.

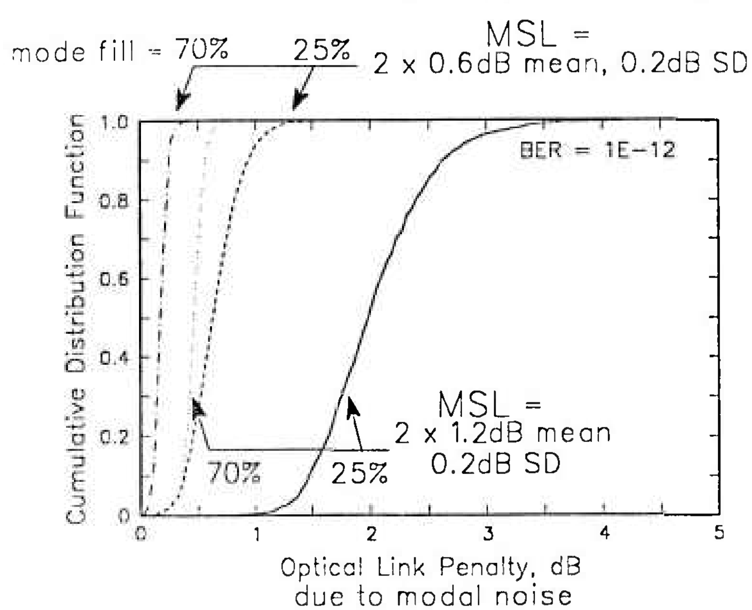
The simulation tool used is valid for noise penalties ≤ 2dB, where it remains reasonable to model the total receiver noise as a Gaussian random variable. Actual high-frequency modal noise has a more negative exponential distribution, so that this analysis will tend to underestimate the severity of the resultant BER floor.

The calculations assume a laser with extinction ration of 1:4, operating principally single-mode, but with occasional mode hopping. This assumes that the transmitter array uses devices like 201/5W, based well above threshold to minimize skew and RIN. It assumes two bulkhead connectors in the link (as proposed by the OETC in the power budget), and a receiver with a threshold detector biased at the mid-signal level. The calculations are made for two connector loss estimates: $\alpha = 0.6$ dB, $\sigma = 0.2$ dB and $\alpha = 1.2$ dB, $\sigma = 0.2$ dB; and for two fiber mode-fill conditions: 25% and 70%. (The actual values will not be known until OETC modules are fabricated.)

Figure 14 shows the results of the statistical simulation of many links assembled from the above components. It plots the cumulative distribution of link penalty versus the link penalty value, so that acceptable link operation occurs when the CDF is ~ 1.0. For mean connector loss of 0.6 dB, the modal noise penalty in the link is < 1.5 dB, even with a poor fiber mode-fill factor of 25%. The AT&T MAC connectors with multimode fibers are anticipated to provide losses below this value, so it was concluded that the OETC link has a safe design point.

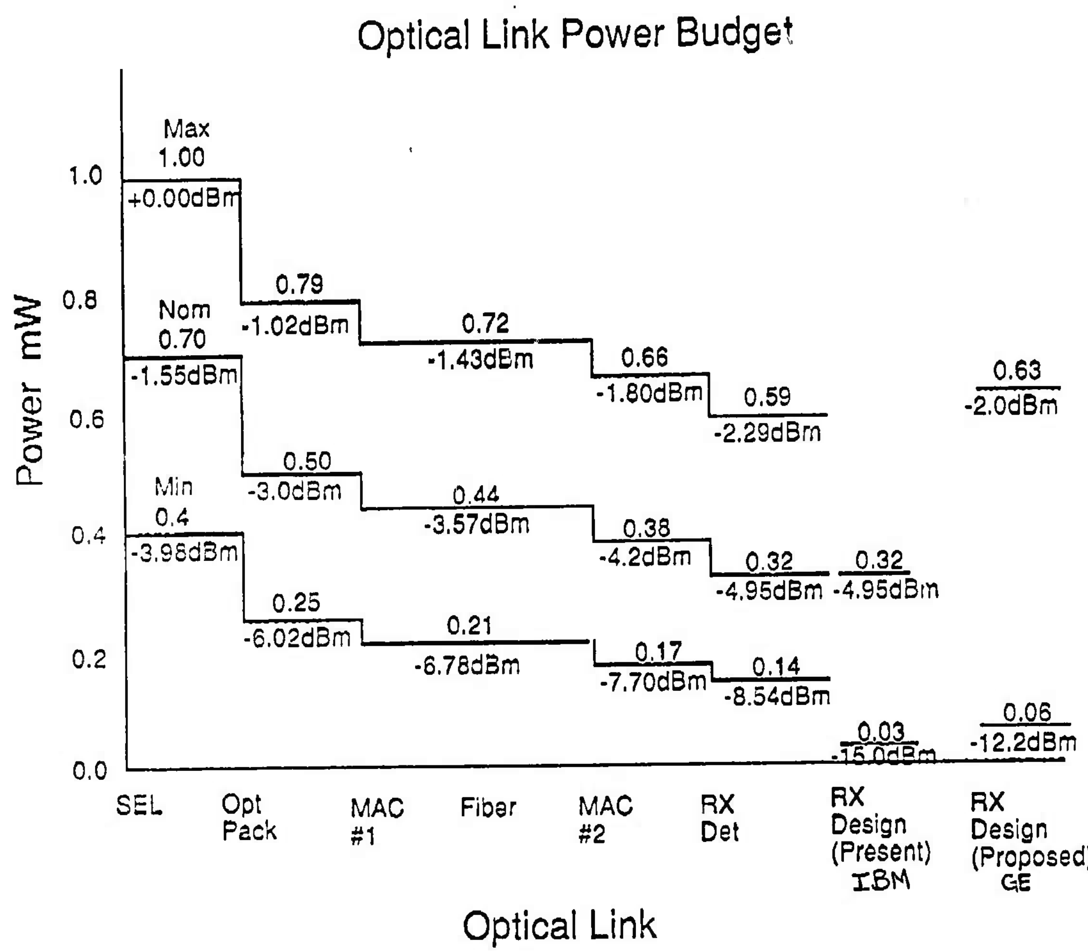
However, if the connector loss goes to 1.2 dB, it is essential to assure a large mode fill factor in the laser to fiber coupling. This is a subject of further investigation when actual OETC parts are assembled.

Figure 14- CDF of optical link penalty for 201/5W like device in the presence of mode-selective loss.



First Pass Link Specification

Based on the above analysis, and experiments, MMC has developed a first pass nominal link power budget, which is shown in Figure 15. The noise sources, and BER effects will be included following testing with first pass parts.



Conclusions and Outstanding Issues

- Simulation predicts that acceptable link should be possible, if first pass component specifications are met. AT&T, MMC, and IBM have agreed to specifications.

- The "single-mode" VSEL design point should be capable of efficient operation with low BER in the OETC link if biased adequately above threshold and the connector loss in the link meets AT&T design specifications.

- A significant amount of high speed characterization should be done on first pass components to get better models for bus simulation. This will require both expensive test equipment, automated data reduction and processing equipment, and experience in characterization. IBM appears to be the only OETC partner with the experience and equipment to execute these tasks in a timely manner, but no responsibility for this mission. A plan is need to resolve this testing exposure.

- Models for the modulator based transmitter and lightguides need to be incorporated into the link simulator.

- Crosstalk models are still needed for the bus simulator, but data from the first pass parts are needed to determine crosstalk parameters to use.

Appendix A - Component Parametric Data

Transmitter Module

Electronics		Nominal	Standard Deviation[1]
Symbol transmission rate, MBaud	:	1000	
Electronics rise time (10-90), ns	:	0.2	
Electronics fall time (90-10), ns	:	0.2	
Electronics low freq "zero", MHz	:	1.0	
Bias current, mA	:	6.7	
Peak-Peak modulation current, mA	:	1.6	

Vertical Surface-Emitting Laser		Nominal[2]	Standard Deviation
Center wavelength, um	:	0.84	
rms spectral width, nm	:	1.0	
Coherence length, m	:	0.5	
Relaxation oscillation freq, GHz	:	3.0	
Damping factor	:	0.5	
Mode partition coefficient	:	0.75	
Relative Intensity Noise, -dB/Hz	:	-120	
RIN "g" coefficient	:	0.5	
Threshold current, mA	:	4.0	
Quantum efficiency, mW/mA	:	0.3	
Fiber coupling efficiency, dB	:	0.6	0.2
Fiber mode fill, %	:	70	

Interconnect

Graded-Index Multimode Fiber		Nominal	Standard Deviation
Operating wavelength, um	:	0.84	
Attenuation, dB/km	:	2.5	
Length, m	:	10.0	
Zero dispersion wavelength, um	:	1.309	
Dispersion slope, ps/km.nm*2	:	0.09576	
Intermodal bandwidth, MHz.km	:	160.0	
Cut-back gamma	:	0.75	
Core diameter, um	:	62.5	
Numerical aperture	:	0.275	
Receiver coupling efficiency, dB	:	0.6	0.2

Receiver Module

MSM-PD/MESFET Transimpedance Amplifier		Nominal	Standard Deviation
Detector responsivity, mA/mW	:	0.35	
Detector dark current, nA	:	5.0	
Detector capacitance, pF	:	0.15	
FET gate-drain capacitance, pF	:	0.02	
FET gate-source capacitance, pF	:	0.16	
FET transconductance, mS	:	3.5	
FET gate leakage current, nA	:	2.0	
FET channel noise factor	:	1.76	
1/f noise frequency, MHz	:	100	
Transimpedance, kΩ	:	3.5	
Equiv. load FET drain resistance kΩ	:	5.0	
FET load capacitance, pF	:	0.05	
Pre-amp temperature, C	:	25	
Post amp l.f. 3dB cut-off, MHz	:	2.0	
Post-amp h.f. 3dB cut-off, GHz	:	1.2	
# of post-amp poles	:	3	
Post-amp gain, dB	:	40	
Sampling latch phase offset, deg	:	0	
Sampling latch amplitude offset, mV	:	0	
Operational BER	:	10^{-12}	

1 Values not included here are to be determined at a later stage in the project
2 Values at 0.5 mW emitted power where applicable